Collection and Analysis of Clear-air Turbulence Data Using an Unmanned Aerial System Alongside a Sodar and UHF Radar

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Project Summary

The goal of this project is to collect and analyze meteorological data using an Unmanned Aerial System (UAS). The data will be collected alongside a sodar and UHF (74-cm wavelength) radar during multiple flights at the Kessler Atmospheric and Ecological Field Station (KAEFS). The UAS will be provided by the Advanced Radar Research Center (ARRC) and the platform used will be the Small Multifunction Autonomous Research and Teaching Sonde (SMARTSonde). The platform was developed to study atmospheric phenomena in the planetary boundary layer (PBL) and is equipped with autopilot, global positioning system (GPS), and meteorological sensors. The SMARTSonde is outfitted with pressure, temperature and humidity sensors. The data obtained will be used to calculate the structure function parameter for temperature (C_T^2) and for refractive index (C_n^2). These parameters will then be compared to sodar and radar-derived values.

Project Narrative

Background

The process of using radio controlled unmanned aircraft to gather atmospheric data has been ongoing since the late 1960s (Konrad et al. 1970). However, it did not gain popularity within the meteorological community due to instrumentation being too large at the time. In recent years, sensors have become much smaller and can easily be deployed in a UAS. This has allowed for several different research institutions to experiment with the UAS platform including researches from Germany, China, and the United States (Chilson et al. 2009).

Starting in the 1990s, the first autonomous UAS to take meteorological measurements was developed and called the Aerosonde (Holland et al. 1992). The platform was capable of measuring temperature, humidity, pressure, trace gas concentrations, and wind among others. As mentioned above, researchers in Germany have developed the Meteorological Mini-UAV (M^2 AV) to collect turbulence and wind vector measurements within the planetary boundary layer (Spiess et al. 2007). Also, the M^2 AV data was compared to data from remote sensing instruments, which is a concept that will be extensively used in this project. The Chinese have developed a UAS as well. Designated as the Robotic Plane Meteorological Sounding System (RPMSS), it is used to acquire atmospheric soundings and thermodynamic profiles in remote areas of China (Shuqing et al. 2004).

At the University of Oklahoma, in conjunction with the Advanced Radar Research Center (ARRC), a UAS platform was first developed in 2009 (Chilson et al. 2009). This platform, called the Small Multifunction Autonomous Research and Teaching Sonde (SMARTSonde), was closely designed after that of a Norwegian research group's UAS platform called SUMO (Small Unmanned

Meteorological Observer) (Reuder et al., 2009) according to Chilson et al. (2009). The SMARTSonde platform is capable of measuring temperature, pressure, humidity, wind speed, and wind direction (Bonin 2011). With these measurements, a thermodynamic and kinematic profile of the planetary boundary layer can be shown.

The entire SMARTSonde platform consists of the Ground Control Station (GCS), the instrumented aircraft, and the radio controller. The GCS can communicate with the aircraft and vice versa which allows for meteorological measurements to be viewed in real time as well as the status of the SMARTSonde including the Global Position System (GPS) location, battery level, and attitude (Bonin 2011). The SMARTSonde uses an autopilot system to fly preprogrammed flight paths. The autopilot system used is called Paparazzi and is free open-source software developed by the French Civil Aviation University (Ecole Nationale De L'Aviation Civile) (Chilson et al. 2009). In full autopilot mode, the Paparazzi system completely controls the aircraft's motion and its flight parameters can be modified with the GCS.

It was mentioned in Konrad et al. (1970) that an experiment to measure clear air turbulence and turbulent mixing would need fine-scale, fast-response measurements that are made possible by a radio-controlled type aircraft. Using the SMARTSonde platform, a more unique data set can be acquired than that of rawinsondes, tethersondes, and meteorological towers. For example, the platform is able to measure clear air turbulence within the PBL with in situ measurements, which can then validate remote sensing instruments such as sodar and lidar.

Project Objective

The first objective of this project is to retrieve data from multiple flights of the SMARTSonde at a remote site. An ideal flight path and helical radius will be determined as well during this process. Once this data has been retrieved, the second objective is to test the theory that these in situ measurements can be used to calculate C_T^2 and C_n^2. If this theory holds, reflectivity will be derived from the structure function and be tested against data from remote sensing equipment.

Description of Project

The direction of this project will begin with data collection. Data will be gathered at KAEFS in McClain County, Oklahoma. KAEFS is an ideal location for this project because of the vast, open space and the presence of several remote sensing devices. Also, in the summer of 2012, The University of Oklahoma obtained the state of Oklahoma's first Certificate of Authorization (COA) from the Federal Aviation Administration (FAA) for civilian operation. This COA allows for unmanned aerial flights at KAEFS up to 3000 feet given that a licensed pilot is present along with two spotters with ground training. Due to this requirement, both authors of this project will be taking a short ground school training course before flights can begin. Flights at KAEFS will consist of a helical ascent, however, the SMARTSonde will be programmed, via autopilot, to maintain level circular flight for a duration of time that allows for multiple complete circular paths before ascending to the next level. This method will be similar to the flight path depicted in Figure 1. The on-board GPS will relate the thermodynamic data to a specific location in space and be transmitted back down to the GCS in real-time.

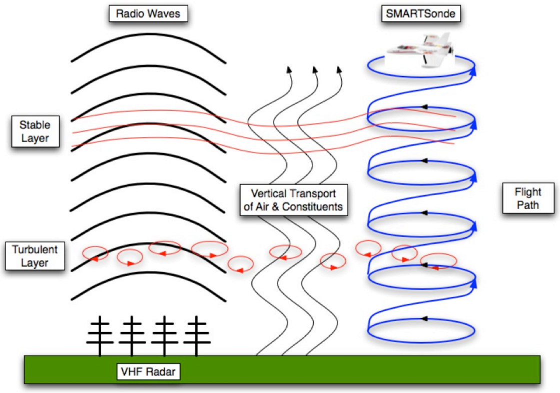

Figure 1: Flight Path

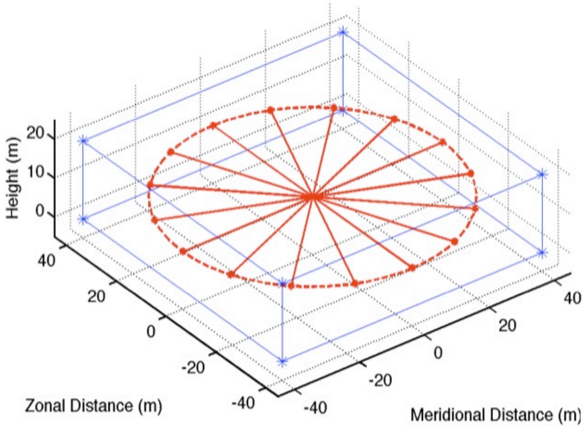

Figure 2

In order to calculate a structure function parameter, numerous instantaneous differences from two points along the perimeter of a disk are needed and then are averaged around the complete disk. However, the SMARTSonde takes about 10 seconds to complete a semi-circle, which could possibly cause an issue with the structure function estimation. This possible error will be taken into account and studied further. Once the data have been acquired, C_T^2 can be directly calculated using the following (Bonin 2011):

$$C_T^2 = \frac{<(T(r_o)-T(r_o+r))^2>}{r^{2/3}} \approx \frac{<(\theta(r_o)-\theta(r_o+r))^2>}{r^{2/3}} \qquad (1)$$

where T is air temperature (K), θ is potential temperature (K), r_o is a position vector at a given height (m), and r is the distance from that position vector (m). Due to the slight fluctuations in altitude during circular flight paths, θ has been substituted for T in Equation 1. C_T^2 will be used further on in the project. Using the SMARTSonde data, the refractive index will be calculated using the following:

$$\mathrm{n} = 1 + 77.6 \times 10^{-6}\,\frac{p}{T} + 0.3733\,\frac{e}{T^2} \tag{2}$$

where p is pressure (hPa), T is temperature (K), and e is water vapor partial pressure (hPa). Once refractive index has been calculated from equation 2, C_n^2 will be determined using the following:

$$C_n^2 = \frac{<(n(r_o) - n(r_o + r))^2>}{r^{2/3}} \tag{3}$$

Because of the computational complexity for a structure function, a programming language will be utilized to calculate C_T^2 and C_n^2 more easily.

If the turbulence being measured meets the four criteria of being isentropic, homogeneous, volume filling, and within the inertial sub range, the reflectivity of an electromagnetic wave at a given wavelength can be calculated with this equation (Atlas 1990):

$$\eta = 0.379\,\lambda^{-1/3}\,C_n^2 \tag{4}$$

where λ is wavelength (m). This theoretical reflectivity will then be compared to the actual reflectivity from on-site radar. Moreover, C_T^2 can be used to calculate the reflectivity of an acoustic wave. Given the same four conditions are met, acoustic reflectivity can be related to the structure function parameter for temperature with this equation:

$$\eta \propto \frac{C_T^2}{T^2} \tag{5}$$

where T is temperature (K). This allows for a direct relationship between our in situ measurements and the remote sensing measurements. If this comparison yields a *constant* proportionality throughout a column of air, we can conclude that the remote measurements accurately depict the sampled volume.

Broader Impact

Measurements of the boundary layer and its evolution are important to meteorology. Remote sensors such as sodar and radar provide a means of boundary layer parameterization that can be very useful for weather model initial conditions. With better initial conditions, more accurate weather forecasts can be formulated. For example, convective initiation relies heavily on PBL processes as small changes can dictate when initiation will occur. Furthermore, anthropogenic air pollutants are occasionally trapped within the PBL, so having accurate sampling of this layer can help forecast the movement of these pollutants.

There is an entire array of remote sensors across the country that is able to collect data constantly in the planetary boundary layer. These sensors provide high resolution PBL profiles which are ingested into forecast models. However, these sensors need to be verified by in situ measurements to testify that they are beneficial to weather forecasting.

Statement of Work

Both members of the group will be participating in data retrieval during the months of December and January. Data analysis will commence in the month of February and continue through March. The results of the study will be expressed in a paper, on a poster and be orally presented in April and May. A brief overview of the future goals are as followed:

1. Retrieval of data (December and January): Both David Goines and Aaron Scott will partake in data collection via SMARTSonde at KAEFS. These flights will likely take place during Christmas break and the early month of January. Complications with the SMARTSonde and/or the inability to acquire a licensed pilot during this time can possibly delay the data collection. Therefore, these flights will be scheduled as soon as possible.
2. Data analysis and calculations (February and March): During this time, David Goines and Aaron Scott will be analyzing the data from the SMARTSonde. A process to efficiently calculate C_T^2 and C_n^2 using a programming language will be determined. Aaron Scott will then begin analyzing C_T^2 using the temperature data once potential temperature has been formulated. Meanwhile, David Goines will be calculating refractive index from the SMARTSonde data and ingesting it into a program that calculates C_n^2. Both members will then come together with these results in order to compare the in situ measured reflectivity to the remote sensing reflectivity.
3. Presentation/Paper (April and May): At the end of the Spring 2013 semester, both team members will summarize the project results on a poster and give presentation. A final paper will also be written.

References

Atlas, D., 1990: *Radar in Meteorology*. American Meteorological Soc., 806.

Bonin, T., 2011: Development and initial application for the SMARTSonde for meteorological research. M.S. thesis. School of Meteorology, The University of Oklahoma, 113 pp.

Chilson, P.B., A. Gleason, B. Zielke, F. Nai, M. Yeary, P. M. Klein, and W. Shalamunec, 2009: SMARTSonde: A small UAS platform to support radar research. *AMS 34th conf. Radar Meteor*., Boston, Mass. Am. Meteorol. Soc.

Holland, G. J., T. McGeer, and H. Youngren, 1992: Autonomous aerosondes for economical atmospheric soundings anywhere on the globe. *Bull. Amer. Meteor. Soc*., **73**, 1987-1998.

Konrad, T., M. Hill, R. Rowland, and J. Meyer, 1970: A small, radio-controlled aircraft as a platform for meteorological sensors. *Appl. Phys. Lab. Tech. Digest*, **10**, 11-19.

Reuder, J., P. Brisset, M. Jonassen, M. Muller, and S. Mayer, 2009: The Small Unmanned Meteorological Observer SUMO: A new tool for atmospheric boundary layer research. *Meteorol.* Z., **18**, 141-147.

Shuqing, M., C. Hongbin, W. Gai, P. Yi, and L. Qiang, 2004: A miniature robotic plane meteorological sounding system. *Advances in Atmospheric Sciences,* **21**, 890-896.

Spiess, T., J. Bange, M. Buschmann, and P. Vorsmann, 2007: First application of the meteorological Mini-UAV 'M^2 AV'. *Meteorol.* Z., **16**, 159-169.